

# Quantum Measurement and the Paulian Idea

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## Abstract

In the quantum Bayesian (or QBist) conception of quantum theory, “quantum measurement” is understood not as a comparison of something pre-existent with a standard, but instead indicative of the creation of something new in the universe: Namely, the fresh experience any agent receives upon taking an action on the world. We explore the implications of this for any would-be ontology underlying QBism. The concept that presently stands out as a candidate “material for our universe’s composition” is “experience” itself, or what John Wheeler called “observer-participancy”.

*Of every would be describer of the universe one has a right to ask immediately two general questions. The first is: “What are the materials of your universe’s composition?” And the second: “In what manner or manners do you represent them to be connected?”*

William James 1988

## 1 Introduction

John Bell famously wrote that the word “measurement” should be banished from fundamental discussions of quantum theory (Bell 1990). In this paper we look at quantum measurement from the perspective of quantum Bayesianism, or “QBism” (Fuchs 2002a, 2004, 2010a, 2013, Caves *et al.* 2007), and argue that the word “measurement” is indeed problematic, even from our perspective. However, the reason it is problematic is not that the word is “unprofessionally vague and ambiguous”, as Bell (1987) said. Rather, it is because the word’s usage engenders a misunderstanding of the subject matter of quantum theory. We say this because from the view of QBism quantum theory is a smaller theory than one might think – it is smaller because it

indicates the world to be a bigger, more varied place than the usual forms of the philosophy of science allow for.

Crucial to the QBist conception of measurement is the slogan – inspired by Peres’ (1978) more famous one – that “unperformed measurements have no outcomes”. Mindful of James’ injunction preceding this article, however, we believe that making precise the intuition behind this slogan is the first step toward characterizing “the materials of our universe’s composition”.

## 2 Bayesian Probabilities

Let us put quantum theory to the side for a moment, and consider instead basic Bayesian probability theory (Savage 1954, de Finetti 1990, Bernardo and Smith 1994, Jeffrey 2004). There the subject matter is an agent’s expectations for this and that. For instance, an agent might write down a joint probability distribution  $P(h_i, d_j)$  for various mutually exclusive hypotheses  $h_i$ ,  $i = 1, \dots, n$ , and data values  $d_j$ ,  $j = 1, \dots, m$ , appropriate to some phenomenon.

A major role of Bayesian theory is that it provides a scheme (Dutch-book coherence, see Vineberg 2011) for how these probabilities should be related to other probabilities,  $P(h_i)$  and  $P(d_j)$  say, as well as to any other degrees of belief the agent has for other phenomena. The theory also prescribes that if the agent is given a specific data value  $d_j$ , he should update his expectations for everything else within his interest. For instance, under the right conditions (Diaconis and Zabell 1982, Skyrms 1987), he should reassess his probabilities for the  $h_i$  by conditionalizing:

$$P_{\text{new}}(h_i) = \frac{P(h_i, d_j)}{P(d_j)} \quad (1)$$

But what is this phrase “given a specific data value”? What does it really mean in detail? Shouldn’t one specify a mechanism or at least a chain of logical or physical connectives for how the raw fact signified by  $d_j$  comes into the field of the agent’s consciousness? And who is this “agent” reassessing his probabilities anyway? Indeed, what is the precise definition of an agent? How would one know one when one sees one? Can a dog be an agent? Or must it be a person? Maybe it should be a person with a PhD?<sup>1</sup>

We are thus led to ask: Should probability theory really be held accountable for giving answers to all these questions? In other words, should a book like *The Foundations of Statistics* (Savage 1954) spend some of its pages

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<sup>1</sup>This is a tongue-in-cheek reference to Bell (1990) again.

demonstrating how the axioms of probability – by way of their own power – give rise, at least in principle, to agents and data acquisition itself? Otherwise, should probability theory be charged with being “unprofessionally vague and ambiguous”?

Probability theory has no chance of answering these questions because they are not questions within the subject matter of the theory. Within probability theory, the notions of “agent” and “given a data value” are primitive and irreducible. Guiding agents’ decisions based on data is what the whole theory is constructed for – just like primitive forces and masses are what the whole theory of classical mechanics is constructed for. As such, agents and data are the highest elements within the structure of probability theory – they are not to be constructed from it, but rather agents are there to receive the theory’s guidance, and the data are there to designate the world external to the agent.

### 3 Quantum Bayesianism

QBism says if all of this is true of Bayesian probability theory in general, it is true of quantum theory as well. As the foundations of probability theory dismiss the questions of where data come from and what constitutes an agent, so can the foundations of quantum theory dismiss them too.

There will surely be a protest from some readers at this point: “It is one thing to say all this of probability theory, but quantum theory is a wholly different story.” Or: “Quantum mechanics is no simple branch of mathematics, be it probability or statistics. Nor can it plausibly be a theory about the insignificant specks of life in our vast universe making gambles and decisions. Quantum mechanics is one of our best theories of the world! It is one of the best maps we have drawn yet of what is actually out there.” But this is where these readers err. We hold fast: Quantum theory is simply *not* a “theory of the world”. Just like probability theory is not a theory of the world, quantum theory is not as well. It is a theory for the use of agents immersed in and interacting with a world of a particular character, the quantum world.

By declaring this, we certainly do not want to dispense with the idea of a world external to the agent. Indeed it must be as Gardner (1983) says:

The hypothesis that there is an external world, not dependent on human minds, made of *something*, is so obviously useful and so strongly confirmed by experience down through the ages that we can say without exaggerating that it is better confirmed than any other empirical

hypothesis. So useful is the posit that it is almost impossible for anyone except a madman or a professional metaphysician to comprehend a reason for doubting it.

Yet there is no implication in these words that quantum theory, for all its success in chemistry, physical astronomy, laser making, and so much else, must be read off as a theory of the world. There is room for a significantly more interesting form of dependence: Quantum theory is conditioned by the character of the world, but yet is not a theory directly of it. Confusion on this point, we believe, is what has caused most of the discomfort in quantum foundations in the 86 years since the theory's coming to a relatively stable form.

## 4 Measurement

Returning to our discussion of Bell and the word “measurement,” it is not because we think it unprofessionally vague and ambiguous that we regard “measurement” as problematic. It is because the word subliminally whispers the philosophy of its birth – that quantum mechanics *should* be conceived in a way that makes no ultimate reference to agency, and that agents are constructed out of the theory, rather than taken as the primitive entities the theory is meant to aid. In a nutshell, the word deviously carries forward the impression that quantum mechanics should be viewed as a theory directly of the world.

One gets a sense of the boundaries the word “measure” places upon our interpretive thoughts by turning to any English dictionary. Here is a sampling from [dictionary.com/](http://dictionary.com/):

- to ascertain the extent, dimensions, quantity, capacity, etc., of, esp. by comparison with a standard;
- to estimate the relative amount, value, etc., of, by comparison with some standard;
- to judge or appraise by comparison with something or someone else;
- to bring into comparison or competition.

In not one of these definitions do we get an image of anything being created in the measuring process; none give any inkling of the crucial contextuality of quantum measurements, the context being a parameter ultimately set only in terms of the agent. Measurement, in its common usage, is something passive and static: it is comparison between *existents*. No wonder a slogan like “unperformed measurements have no outcomes” (cf. Peres 1978) would

seem irreparably paradoxical. If a quantum measurement is not comparison, but something else, the only way out of the impasse is to understand what that something else is.

Correcting or modifying the word “measurement” is the prerequisite to a new ontology – in other words, prerequisite to a statement about the (hypothesized) character of the world that does not make direct reference to our actions and gambles within it. Therefore, as a start, let us rebuild quantum mechanics in terms more conducive to the QBism program. The best way to begin a more thoroughly delineation of quantum mechanics is to start with two quotes on personalist Bayesianism itself. The first is from Hampton *et al.* (1973):

Bruno de Finetti believes there is no need to assume that the probability of some event has a uniquely determinable value. His philosophical view of probability is that it expresses the feeling of an individual and cannot have meaning except in relation to him.

And the second is from Lindley (1982):

The Bayesian, subjectivist, or coherent, paradigm is egocentric. It is a tale of one person contemplating the world and not wishing to be stupid (technically, incoherent). He realizes that to do this his statements of uncertainty must be probabilistic.

These two quotes make it clear that personalist Bayesianism is a “single-user theory”. Thus, QBism must inherit at least this much egocentrism in its view of quantum states  $\rho$ . The “Paulian idea” (Fuchs 2010b) – which is also essential to the QBist view – goes further still (cf. Figure 1). It says that the outcomes of quantum measurements are single-user as well! That is to say, when an agent writes down her degrees of belief for the outcomes of a quantum measurement, what she is writing down are her degrees of belief about her potential *personal* experiences arising in consequence of her actions upon the external world.

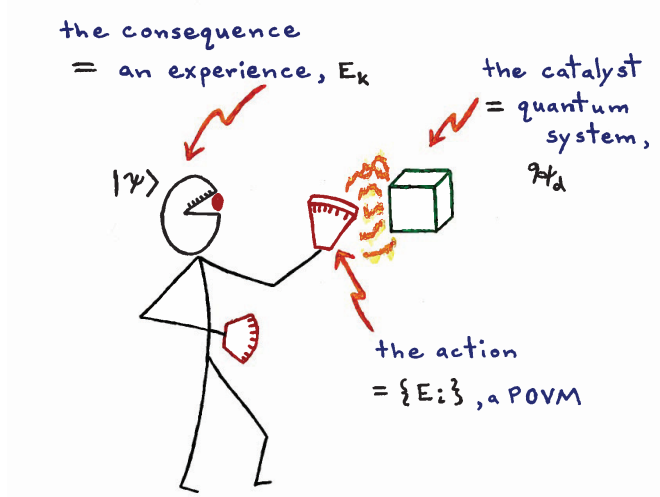


Figure 1: The Paulian Idea (Fuchs 2010b) – in the form of a figure inspired by John Archibald Wheeler, whose vision of quantum mechanics has been greatly inspiring to us, and overtones of his thought can be found throughout our own. The figure of his that suggested the present one can be found in Patton and Wheeler (1975), Wheeler and Patton (1977), Wheeler (1979), Wheeler (1980), Wheeler (1982), Wheeler (1994).

In contemplating a quantum measurement (though the word is a misnomer), one makes a conceptual split in the world: one part is treated as an agent, and the other as a kind of reagent or catalyst (one that brings about change in the agent itself). In older terms, the former is an observer and the latter a quantum system of some finite dimension  $d$ . A quantum measurement consists first in the agent taking an *action* on the quantum system. The action is formally captured by some positive operator valued measure  $\{E_i\}$  (POVM, cf. footnote 2 below). The action leads generally to an incompletely predictable *consequence*, a particular personal experience  $E_i$  for the agent (Fuchs 2007, 2010a). The quantum state  $|\psi\rangle$  makes no appearance but in the agent's head; for it only captures his degrees of belief concerning the consequences of his actions, and – in contrast to the quantum system itself – has no existence in the external world. Measurement devices are depicted as prosthetic hands to make it clear that they should be considered an integral part of the agent. (This contrasts with Bohr's view where the measurement device is always treated as a classically describable system external to the observer.) The sparks between the measurement-device hand and the quantum system represent the idea that the consequence of each quantum measurement is a unique creation within the previously existing universe (Fuchs 2010a, 2013). Wolfgang Pauli characterized this picture as a “wider form of the reality concept” than that of Einstein's, which he labeled “the ideal of the detached observer” (Pauli 1994, Laurikainen 1988, Gieser 2005).

## 5 Basic Notions of Quantum Theory from a QBist Point of View

Before exploring this further, let us partially formalize in a quick outline the structure of quantum mechanics from the Bayesian point of view. At the moment we will retain the usual mathematical formulation of the theory, but we will begin the process of changing the verbal description of what the term “quantum measurement” means.

1. Primitive notions: a) the agent, b) things external to the agent, or, more commonly, “systems,” c) the agent’s actions on the systems, and d) the consequences of those actions for her experience.
2. The formal structure of quantum mechanics is a theory of how the agent ought to organize her Bayesian probabilities for the consequences of all her potential actions on the things around her. Implicit in this is a theory of the structure of actions. This works as follows.
3. When the agent posits a system, she posits a Hilbert space  $\mathcal{H}_d$  of dimension  $d$  as the arena for all her considerations.
4. Actions upon the system are captured by positive-operator valued measures  $\{E_i\}$ , briefly POVMs,<sup>2</sup> on  $\mathcal{H}_d$ . Potential consequences of the action are labeled by the individual elements  $E_i$  within the set. That is,

$$\text{ACTION} = \{E_i\} \quad \text{and} \quad \text{CONSEQUENCE} = E_k .$$

5. Quantum mechanics organizes the agent’s beliefs by saying that she should strive to find a single density operator  $\rho$  such that her degrees of belief will always satisfy

$$\begin{aligned} \text{Prob}(\text{CONSEQUENCE} \mid \text{ACTION}) &= \text{Prob}(E_k \mid \{E_i\}) \\ &= \text{Trace } \rho E_k , \end{aligned}$$

no matter what action  $\{E_i\}$  is under consideration.

6. Unitary time evolution and more general quantum operations (completely positive maps) do not represent objective underlying dynamics, but rather address the agent’s belief changes accompanying the flow of time, as well as belief changes consequent upon any actions taken.

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<sup>2</sup>See, e.g., Berberian (1966) for a precise definition. In contrast to a projection-valued measure (projector) with characteristic function  $\{0,1\}$  and orthogonal eigenfunctions, the characteristic function of a POVM is the entire interval  $[0,1]$ , and the eigenfunctions are generally not orthogonal. POVMs generalize the idealized idea of quantum measurements as projections and lead to a more realistic picture.

7. When the agent posits *two* things external to herself, the arena for all her considerations becomes  $\mathcal{H}_{d_1} \otimes \mathcal{H}_{d_2}$ . Actions and consequences now become POVMs on  $\mathcal{H}_{d_1} \otimes \mathcal{H}_{d_2}$ .
8. The agent can nonetheless isolate the notion of an action on a single one of the things alone: These are POVMs of the form  $\{E_i \otimes I\}$ , and similarly with the systems reversed  $\{I \otimes E_i\}$ .
9. Resolving the consequence of an action on *one* of the things may cause the agent to update her expectations for the consequences of any further actions she might take on the *other* thing. But for those latter consequences to come about, she must elicit them through an actual action on the second system.

With regard to the present discussion, the main points to note are items 4, 7, 8, and 9. Regarding our usage of the word “measurement,” they say that one should think of it simply as an *action* upon the system of interest. Actions lead to consequences within the experience of the agent, and that is what a quantum measurement is. A quantum measurement finds nothing, but very much *makes* something.

It is a simple linguistic move, but it does crucial work for resetting the debate on quantum foundations. It might indeed have been the case that all this nonstandard formulation was for nought, turning out to be superfluous. That is, though we have spelled out very carefully in item 9 that, “for those latter consequences to come about, she must elicit them through an actual action on the second system”, maybe there would have been nothing wrong in thinking of the latter (and by analogy the former) quantum measurement as finding a pre-existing value after all. But this, we have argued previously (Caves 2007, Fuchs 2013) would contradict item 8, i.e., that one can isolate a notion of an action on a single system alone.

Thus, in a QBist painting of quantum mechanics, quantum measurements are “generative” in a very real sense. But by that turn, the consequences of our actions on physical systems must be egocentric as well. Measurement outcomes come about for the agent herself. Quantum mechanics is a single-user theory through and through – first in the usual Bayesian sense with regard to personal beliefs, and second in that quantum measurement outcomes are wholly personal experiences.<sup>3</sup>

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<sup>3</sup>The usual belief otherwise – for instance in Pauli’s own formulation (which is ultimately inconsistent with his taking measurement devices to be like prosthetic hands), that “the objective character of the description of nature given by quantum mechanics [is] adequately guaranteed by the circumstance that ... the results of observation, *which can be checked by anyone*, cannot be influenced by the observer, once he has chosen his experimental



Of course, as a single-user theory, quantum mechanics is available to any agent to guide and better prepare her for her own encounters with the world. And although quantum mechanics has nothing to say about another agent’s personal experiences, agents can communicate and use the information gained from each other to update their probability assignments. In the spirit of the Paulian idea, however, querying another agent means taking an action on him.

Whenever “I” encounter a quantum system, and take an action upon it, it catalyzes a consequence in my experience that my experience could not have foreseen. Similarly, by a Copernican-style principle, I should assume the same for “you”: Whenever you encounter a quantum system, taking an action upon it, it catalyzes a consequence in your experience. By one category of thought we are agents, but by another category of thought we are physical systems. And when we take actions upon each other, the category distinctions are symmetrical. Like with the bistable perception of ambiguous images (e.g., the Rubin vase), the best the eye can do is flit back and forth between the two formulations.

## 6 The World View of QBism

The previous paragraphs should have made clear that viewing quantum mechanics as a single-user theory does not mean there is only one user. QBism does not lead to solipsism. Any charge of solipsism is further refuted by two points central to the Paulian idea (Fuchs 2002b). One is the conceptual split of the world into two parts – one an agent and the other an external quantum system – that gets the discussion of quantum measurement off the ground in the first place. If such a split were not needed for making sense of the question of actions (actions upon what? in what? with respect to what?), it would not have been made. Imagining a quantum measurement without an autonomous quantum system participating in the process would be as paradoxical as the Zen koan of the sound of a single hand clapping.

The second point is that once the agent chooses an action  $\{E_i\}$ , the particular consequence  $E_k$  of it is beyond his control. That is to say, the particular outcome of a quantum measurement is not a product of his desires, whims, or fancies – this is the very reason he uses the calculus of probabilities in the first place: they quantify his uncertainty (Lindley 2006),

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arrangement” (Pauli 1956, italics ours, to pinpoint the offending portion of the formulation) – we state for completeness, is the ultimate source of the Wigner’s friend paradox. This will be expanded upon in a later work by the authors; for the moment see Fuchs (2013).

an uncertainty that, try as he might, he cannot get around. So, implicit in this whole picture – this whole Paulian idea – is an “external world . . . made of *something*,” just as Gardner calls for. It is only that quantum theory is a rather small theory: Its boundaries are set by being a handbook for agents immersed within that “world made of *something*”.

But a small theory can still have grand import, and quantum mechanics most certainly does. This is because it tells us how a user of the theory sees his role in the world. Even if quantum mechanics – viewed as an addition to probability theory – is not a theory of the world itself, it is certainly conditioned by the particular character of this world. Its empirical content is exemplified by the Born rule, item 5 in the above list, which takes a specific form rather than an infinity of other possibilities. Even though quantum theory is now understood as a theory of acts, decisions, and consequences (Savage 1954), it tells us, in code, about the character of our particular world. Apparently, the world is made of a stuff that does not have “consequences” waiting around to fulfill our “actions” – it is a world in which the consequences are generated on the fly. When we on the inside prod that stuff on the outside, the world comes to something that neither side could have foretold.

Indeed, one starts to get a sense of a world picture that is part personal – *truly* personal – and part the joint product of all that interacts. It is almost as if one can hear in the very formulation of the Born rule one of William James’ many lectures on chance and indeterminism. Here is one example (James 1956a):

[Chance] is a purely negative and relative term, giving us no information about that of which it is predicated, except that it happens to be disconnected with something else – not controlled, secured, or necessitated by other things in advance of its own actual presence. . . . What I say is that it tells us nothing about what a thing may be in itself to call it “chance.” . . . All you mean by calling it “chance” is that this is not guaranteed, that it may also fall out otherwise. For the system of other things has no positive hold on the chance-thing. Its origin is in a certain fashion negative: it escapes, and says, Hands off! coming, when it comes, as a free gift, or not at all.

This negativeness, however, and this opacity of the chance-thing when thus considered *ab extra*, or from the point of view of previous things or distant things, do not preclude its having any amount of positiveness and luminosity from within, and at its own place and moment. All that its chance-character asserts about it is that there is something in it really of its own, something that is not the unconditional property of the whole. If the whole wants this property, the whole must wait till it can get it, if it be a matter of chance. That the universe may actually

be a sort of joint-stock society of this sort, in which the sharers have both limited liabilities and limited powers, is of course a simple and conceivable notion.

And here is another (James 1956b):

Why may not the world be a sort of republican banquet of this sort, where all the qualities of being respect one another's personal sacredness, yet sit at the common table of space and time?

To me this view seems deeply probable. Things cohere, but the act of cohesion itself implies but few conditions, and leaves the rest of their qualifications indeterminate. As the first three notes of a tune comport many endings, all melodious, but the tune is not named till a particular ending has actually come, – so the parts actually known of the universe may comport many ideally possible complements. But as the facts are not the complements, so the knowledge of the one is not the knowledge of the other in anything but the few necessary elements of which all must partake in order to be together at all. Why, if one act of knowledge could from one point take in the total perspective, with all mere possibilities abolished, should there ever have been anything more than that act? Why duplicate it by the tedious unrolling, inch by inch, of the foredone reality? No answer seems possible. On the other hand, if we stipulate only a partial community of partially independent powers, we see perfectly why no one part controls the whole view, but each detail must come and be actually given, before, in any special sense, it can be said to be determined at all. This is the moral view, the view that gives to other powers the same freedom it would have itself, – not the ridiculous “freedom to do right”, which in my mouth can only mean the freedom to do as *I* think right, but the freedom to do as *they* think right, or wrong either.

This is a world of “objective indeterminism” indeed, but one with no place for “objective chance” in the sense of David Lewis (1986). From within any part, the future is undetermined. If one of those parts is an agent, then it is an agent in a situation of uncertainty. And where there is uncertainty, agents should use the calculus of Bayesian probability in order to make the best go at things.

But we have learned enough from Copernicus to know that egocentrism, whenever it can be shaken away from a *Weltanschauung*, it ought to be. Whenever “I” encounter a quantum system, and take an action upon it, it catalyzes a consequence in my experience that my experience could not have foreseen. Similarly, by a Copernican principle, I should assume the same for “you”: Whenever you encounter a quantum system, taking an action upon it, it catalyzes a consequence in your experience. By one category of thought,

we are agents, but by another category of thought we are physical systems. And when we take actions upon each other, the category distinctions are symmetrical.

In the common circles of the philosophy of science there is a strong popularity in the idea that agentialism can always be reduced to some complicated property arrived at from physicalism. But perhaps this republican-banquet vision of the world that so seems to fit a QBist understanding of quantum mechanics is telling us that the appropriate ontology we should seek would treat these dual categories as just that, dual aspects of a higher, more neutral realm.<sup>4</sup> That is, the concepts “action” and “unforeseen consequence in experience”, both crucial for clarifying the very meaning of quantum measurement, might just be applicable after a fashion to arbitrary components of the world – i.e., venues in which probability talk has no place. Understanding or rejecting this idea is the long road ahead of us.

We leave an old teacher of ours with some closing words that touch on the challenge William James started us off with:

*It is difficult to escape asking a challenging question. Is the entirety of existence, rather than being built on particles or fields of force or multidimensional geometry, built upon billions upon billions of elementary quantum phenomena, those elementary acts of “observer-participancy”, those most ethereal of all the entities that have been forced upon us by the progress of science?*

John Archibald Wheeler 1982

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<sup>4</sup>For a few further suggestive things to read in this regard, we propose James (1940, 1996), Lamberth (1999), Taylor and Wozniak (1996), Wahl (1925). Neutral monism and dual-aspect monism have become influential frameworks of thinking in contemporary discussions in the philosophy of mind (cf. Velmans and Nagasawa 2012).

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